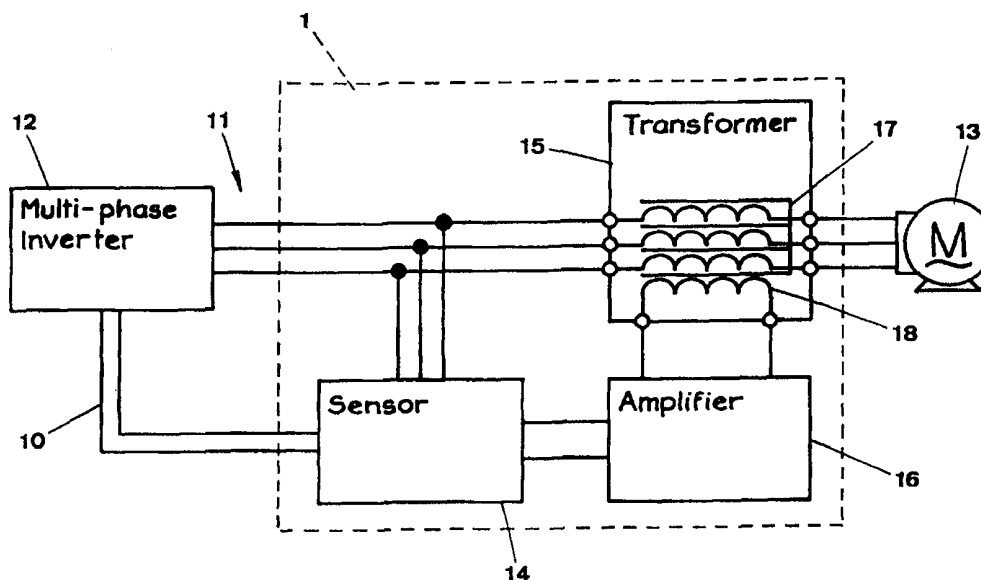




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(54) Title: IMPROVEMENTS RELATING TO POWER INVERTERS



(57) Abstract

Systems which enable common mode effects in high power inverter arrangements to be compensated using relatively low power electronic components. A sensor detects the effects in phase supply leads which connect in inverter to an electric machine. This produces a compensation signal which is stepped up and coupled back into the leads by way of a transformer. Common mode voltages in the leads may be detected using a substantially resistive network, for example.

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IMPROVEMENTS RELATING TO POWER INVERTERS

FIELD OF THE INVENTION

- 5 This invention relates to active compensation of common-mode components which may appear in the output of multi-phase power conversion systems, and particularly but not solely to compensation systems which are suitable for high power inverters.

BACKGROUND TO THE INVENTION

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Multi-phase PWM inverters are often used to control electric machines such as three-phase cage induction motors. The inverter switches voltage pulses into the stator of the motor at frequencies typically in the range 1 to 40 kHz. This switching produces unwanted common-mode voltage and current components in the phase supply leads which connect the inverter
15 to the motor. The currents emit electromagnetic interference at the switching frequencies and higher harmonics. The voltages couple between the stator, the rotor and the motor frame by way of parasitic capacitances to produce leakage currents, some of which reach ground through the rotor bearings. Such bearing currents generate localised heating which can damage the bearings and cause failure of the motor.

20

Various techniques have been tried to reduce these emissions and prevent buildup of voltage in the rotor, including passive and active filters which may be connected in the output of an inverter. Passive techniques require relatively large and expensive filter arrangements to operate at higher power levels. One active technique involving a common-mode transformer
25 is described in JP 10094244 and appears effective at only moderate power levels. A sensor feeds the common-mode voltage into an excitation winding in the transformer which couples to the phase windings with a turns ratio of 1:1. This feeds the voltage back into the supply leads with opposite polarity to thereby compensate and ideally cancel the common-mode current flowing into the motor.

30

Techniques involving common-mode transformers have so far been impractical where power requirements of the motor are greater than about 10 kW and dc link voltages to the inverter are greater than about 400V. The common-mode components are typically sensed by capacitor arrangements and connected through simple push-pull emitter-follower stages
35 to drive the excitation winding of the 1:1 transformer. This circuitry limits the bandwidth of the compensation action so that common-mode components having high frequencies up to around 1 MHz or more, remain in the motor supply.

A comparison of various filter techniques which have been used to reduce common-mode noise is given by Jorgensen et al., PCIM 1998, Conference Proceedings, p273-280.

SUMMARY OF THE INVENTION

5

It is therefore an object of the present invention to provide alternative systems for cancellation or at least reduction of common-mode voltages produced by high power multi-phase inverters.

10

Accordingly the invention may broadly be said to consist in methods and apparatus by which common-mode components are sensed in the inverter output to produce a relatively low voltage compensation signal. This signal can be coupled back into the output at a voltage which opposes the common-mode components, using relatively low power electronic devices.

15

In one aspect the invention may be said to consist in a method of reducing common-mode components output by a multi-phase inverter, including: sensing the components in phase supply leads connecting the inverter to an electric machine and producing a compensation signal of relatively low magnitude, coupling the compensation signal to the supply leads using a transformer at a polarity opposite to that of the common-mode components, and increasing the magnitude of the compensation signal in the transformer to match that of the common-mode components.

20

In another aspect the invention may be said to consist in apparatus for reducing a common-mode voltage output by a multi-phase inverter, including: sensor means for detecting the voltage in phase supply leads which connect the inverter to an electric machine and for producing a detection signal, amplifier means for receiving the detection signal and producing a corresponding voltage compensation signal, and transformer means for increasing and coupling the compensation signal to the phase supply leads at a voltage substantially opposed to the common mode voltage.

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30

BRIEF LIST OF FIGURES

Preferred embodiments of the invention will be described with reference to the drawings, of which:

35

Figures 1a and 1b are schematic diagrams showing filter systems for reduction of common-mode output from an inverter,

Figure 2 shows more detail of a system according to Figure 1a,

Figure 3 shows a coaxial transformer which may be used in these systems,
Figures 4a and 4b are alternative systems having transformers in parallel,
Figure 5 shows an alternative transformer arrangement, and
Figure 6 is a dual filter system for low and high frequency common-mode
5 components.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to the drawings it will be appreciated that our solution to the problem of common-
10 mode components produced by switching in multi-phase power conversion devices may be
implemented in various forms. The following description is given by way of example only.

Figures 1a and 1b show the invention as alternative filtering systems 1 and 2 respectively,
each connected in a set of three-phase supply leads 11 by which an inverter 12 provides
15 power to an electric machine such as an induction motor 13. The systems each include a
common-mode sensor 14 which produces a compensation signal for a filter 15 in the form
of a transformer. An amplifier 16 is also normally included as a distinct element but may
alternatively be considered as part of the sensor or filter devices. The sensor may be said
to produce a detection signal for the amplifier. Either system may be manufactured as part
20 of the inverter, or possibly as part of the motor, or may be retrofitted to an existing inverter
or motor arrangement. Operation of inverters and motors will be understood by a skilled
reader and need not be described in detail.

In Figure 1a the sensor 14 detects common-mode voltage at a range of frequencies in the
25 leads 11 and produces a low voltage image signal for the amplifier 16. The sensor
preferably has a high input impedance so as not to affect control of the motor by the inverter,
and a suitably low output impedance so as to drive the amplifier without undue limitation
of bandwidth. The amplifier drives the transformer 15 to produce a voltage in the leads 11
which opposes the common-mode voltage as detected by the sensor. Power for the amplifier
30 is drawn from the inverter on leads 10. A high bandwidth power amplifier is preferably
used between the sensor and transformer, such as one of a range of simple class A or AB
devices which are readily available. The low voltage output by the sensor and the broad
bandwidth of the amplifier enable the system to compensate common-mode voltages
produced by relatively high power inverters.

35

The filter 15 in Figure 1a has three phase windings 17 each connected in series with a
respective supply lead 11, and is often termed a common-mode transformer. The amplifier
is shown connected to the excitation winding so as to reverse the polarity of a compensation

signal which is generated with increased voltage in the phase windings. This injects the compensation signal back into the phase supply leads to oppose the common-mode voltage, although the opposition of voltage could also be achieved by a phase shift in the amplifier itself, or in other ways. In this example there is just a single excitation winding 18 which
5 couples flux with each phase winding, preferably in the form of a coaxial transformer as described further below. Differential mode flux components add to zero in such an arrangement although other arrangements are possible as also indicated below. In general however, the excitation and phase windings are selected with a step-up turns ratio to increase the magnitude of the compensation signal which is received from the amplifier 16.

10 In system 1 of Figure 1a, the sensor 12, amplifier 16 and transformer 15 create a feed-forward loop having a gain of -1 for the common-mode voltage. In system 2 of Figure 1b, the transformer is connected in the supply leads before the sensor to create a feed-backwards loop. The former arrangement is preferred as the latter will generally require additional
15 feedback control components. However, a combined feed-forward and feed-backward system may be envisaged whereby common-mode components are sensed both before and after the filtering action of the transformer. In this embodiment a high bandwidth feed-forward loop produces the compensation signal for the transformer and a relatively slow acting feedback controller may be used to fine tune the feed-forward amplifier.

20 When considering the system of either Figure 1a or 1b the sensor 12, amplifier 16 and transformer 15 may be considered as having gains of A_1 , A_2 and A_3 respectively. The product A_2A_3 is generally inversely related to A_1 , so that $A_1A_2A_3 = -1$, and the transformer induces a voltage in the supply leads which substantially cancels that detected by the sensor.
25 By way of example, a common-mode voltage of perhaps 100V rms would be typical in the output of many high power inverters. Sensor 12 would attenuate this voltage to produce a relatively low magnitude compensation signal of perhaps 1V rms. Amplifier 16 would increase the signal to perhaps 10V and the transformer 15 would then increase the signal still further to 100V through a step-up ratio of 1:10.

30 Figure 2 shows some additional detail of a system 3 according to Figure 1a. Sensor 12 includes an impedance network 21 connected to each phase supply lead 11 from the inverter, and a buffer 22. The network may be a simple resistive divider with a neutral point 23 from which the buffer picks up a signal proportional to the common-mode voltage on the leads.
35 Normal differential phase voltages output by the inverter add to zero at this point. Amplifier 16 receives the signal from the buffer and in turn drives the excitation winding 18 of common-mode transformer 15. The amplifier is fed by a power supply 25 which is connected through lines 10 to high voltage dc bus terminals in the inverter. The transformer

is connected back to the inverter through the midpoint of a capacitor pair 26 which limit dc and low frequency currents in the excitation winding.

5 The filter system in Figure 2 is constructed to be capable of retrofit to existing inverter equipment. Ground connections are made from the resistive network 21, the excitation winding 18, and the capacitor pair 26 to an existing earth conductor which is connected between the inverter and the motor. A suitable capacitor midpoint might not otherwise be available. It should also be noted that the system as shown is intended to compensate only for common-mode components which are produced by switching in the inverter, rather than
10 relatively low frequency components produced by the rectifier which provides input to the inverter. A connection to ground rather than through the capacitor pair 26 would enable compensation of common-mode components produced by the rectifier.

Figure 3 shows a preferred coaxial transformer which may be used as the filter in systems
15 such as those shown in Figures 1a and 1b. A large voltage step-up is possible in transformers of this kind which enables reasonably cheap low voltage sensor and amplifier elements to be used elsewhere in the system. The transformer core may be provided by a double stack 30 of toroidal ferrite cores 31 which are readily available. A single excitation winding is then formed as a connected pair of tubular linings 32 in the stacks. The phase
20 windings 33 are then multi-filar wound together through the linings. Current is input and output from the excitation winding through terminals 34, and from the phase windings through multi-phase terminals 35.

The number of multi-phase windings 33 in Figure 3 should be maximised for a given
25 internal diameter of the toroidal cores 31. This assists to minimise the number of cores required to avoid saturation. However, the use of standard cores limits the number of phase windings and therefore the current carrying capacity of a single system. Multiple systems may therefore be combined in parallel to give a desired current rating, as indicated below.

30 Figures 4a and 4b show how a system according to Figure 1a may be expanded or multiplied to accommodate high currents produced by the inverter 12 for a motor 13. In Figure 4a a common-mode compensation system 4 includes two transformers connected in parallel between the inverter and motor. Sensor 14 and power amplifier 16 provide a compensation signal to both transformer 15 and the additional transformer 40. A single connection 10 to
35 the inverter feeds a power supply for the amplifier which must be capable of driving the two excitation windings. In Figure 4b two complete systems 1 are ganged in parallel.

Figure 5 shows a further filtering system 5 in which the phase supply leads 11 between inverter 12 and motor 13 are individually compensated. Three separate excitation windings 51 and phase windings 52 are provided in a transformer block 50. Amplifier 56 is constructed to drive the excitation windings with individual compensation signals. One possible disadvantage of this system is an increase in transformer weight and complexity.

Figure 6 shows a complete drive arrangement for an electric machine 13, including three-phase supply 7, rectifier 8, inverter 12 and supply leads 11. A combination of two filter systems is connected in series in the supply leads for compensating a broader range of common-mode components which appear in the inverter output. System 1 compensates high frequency components produced by inverter switching as described above. System 6 compensates relatively low frequency components produced by the rectifier.

System 6 of Figure 6 is generally similar to system 1, including sensor 64, amplifier 66 with power supply fed from the inverter by leads 10, and transformer 65, suitable for low frequency signals. In particular the transformer 66 will be larger and heavier than transformer 15, and additional earth connections 67 for the power supply and output of the excitation winding are now explicitly shown.

CLAIMS:

1. A method of reducing common-mode components output by a multi-phase inverter, including:
 - 5 sensing the components in phase supply leads connecting the inverter to an electric machine and producing a compensation signal of relatively low magnitude,
 - coupling the compensation signal to the supply leads at a polarity opposite to that of the common-mode components using a transformer, and
 - 10 increasing the magnitude of the compensation signal in the transformer to match that of the common-mode components.
2. A method according to claim 1 wherein sensing the common-mode components includes:
 - 15 sensing common-mode voltage using a substantially resistive network connected to each of the phase supply leads.
3. A method according to claim 1 wherein coupling the compensation signal to the supply leads includes:
 - 20 increasing the magnitude of the signal using a power amplifier which drives an excitation winding in the transformer.
4. A method according to claim 1 wherein increasing the magnitude of the compensation signal in the transformer includes:
 - 25 stepping up the magnitude using a one-turn excitation winding which couples to each phase winding in the transformer.
5. A method according to claim 1 wherein the compensation signal is coupled to the supply leads by coaxial transformer.
- 30 6. A method according to claim 1 wherein the compensation signal is coupled to the supply leads by a plurality of transformers in parallel.
7. A method according to claim 1 wherein the common-mode components are sensed upstream of the transformer in the supply leads.
- 35 8. A method according to claim 1 wherein the common-mode components are sensed downstream of the transformer in the supply leads.

9. Apparatus for reducing common-mode voltage output by a multi-phase inverter, including:

5 sensor means for detecting the voltage in phase supply leads which connect the inverter to an electric machine and for producing a detection signal,

amplifier means for receiving the detection signal and producing a corresponding voltage compensation signal, and

transformer means for increasing and coupling the compensation signal to the supply leads at a voltage substantially opposed to the common mode voltage.

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10. Apparatus according to claim 9 wherein the sensor and amplifier means have a combined gain and the transformer means has a step-up gain which are inversely related.

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11. Apparatus according to claim 9 wherein the transformer means has a step-up turns ratio of $N > 1$ and the sensor and amplifier means have a combined a gain of substantially $1/N$.

12. Apparatus according to claim 9 wherein the sensor means includes a substantially resistive network connected to the supply leads.

20

13. Apparatus according to claim 9 wherein the transformer means includes a coaxial transformer having a one-turn excitation winding.

14. Apparatus according to claim 9 including a plurality of transformer means connected in parallel.

25

15. Apparatus according to claim 9 including a plurality of transformer means connected in series.

30

16. A method of reducing common-mode components substantially as herein described with reference to the accompanying drawings.

17. Apparatus for reducing a common-mode voltage substantially as herein described with reference to the accompanying drawings.

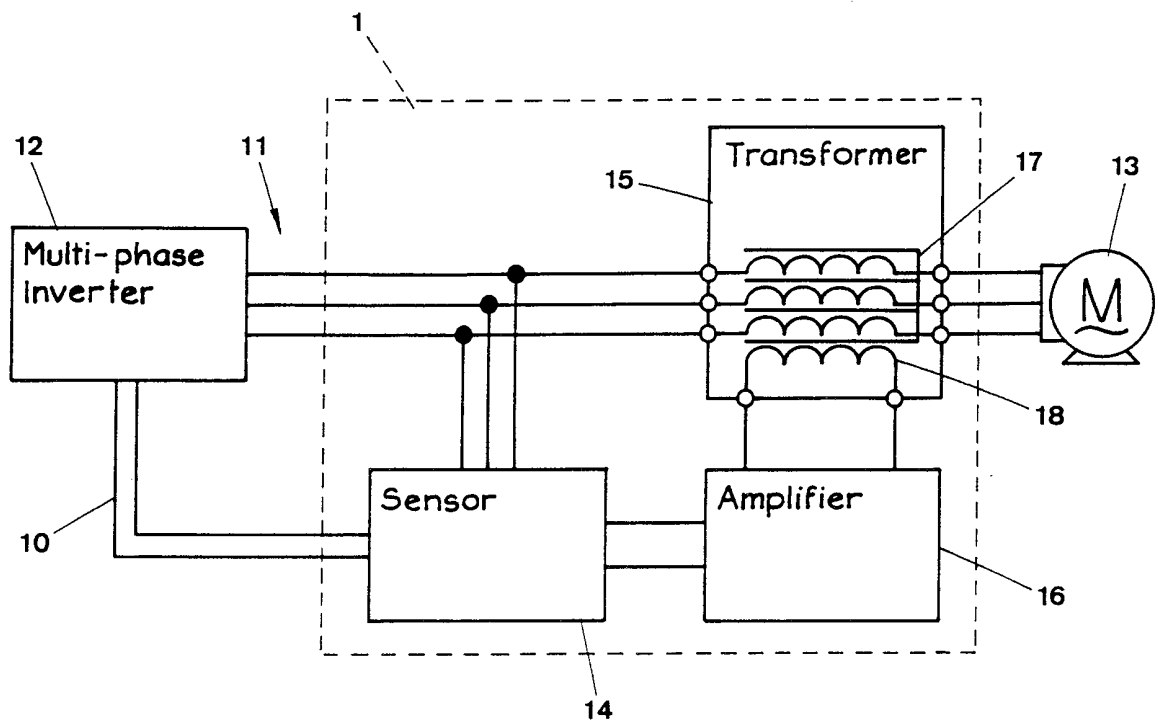


Figure 1a

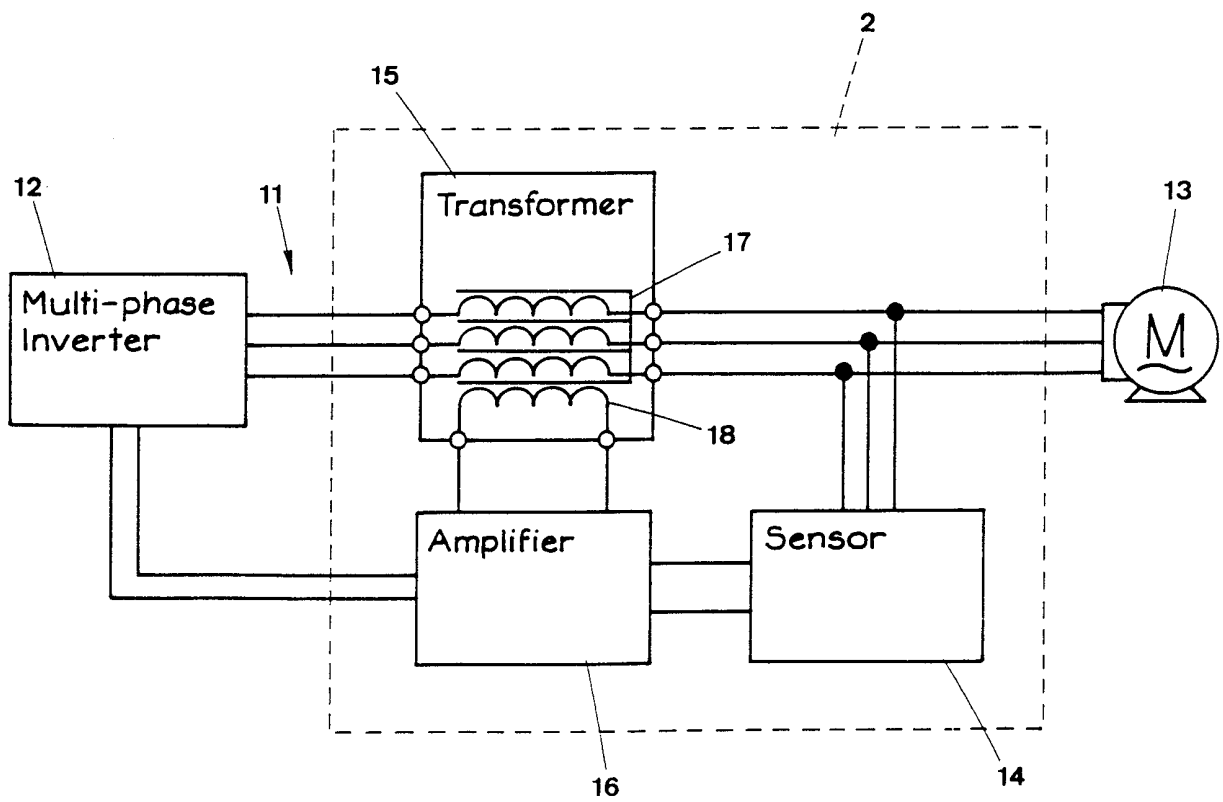


Figure 1b

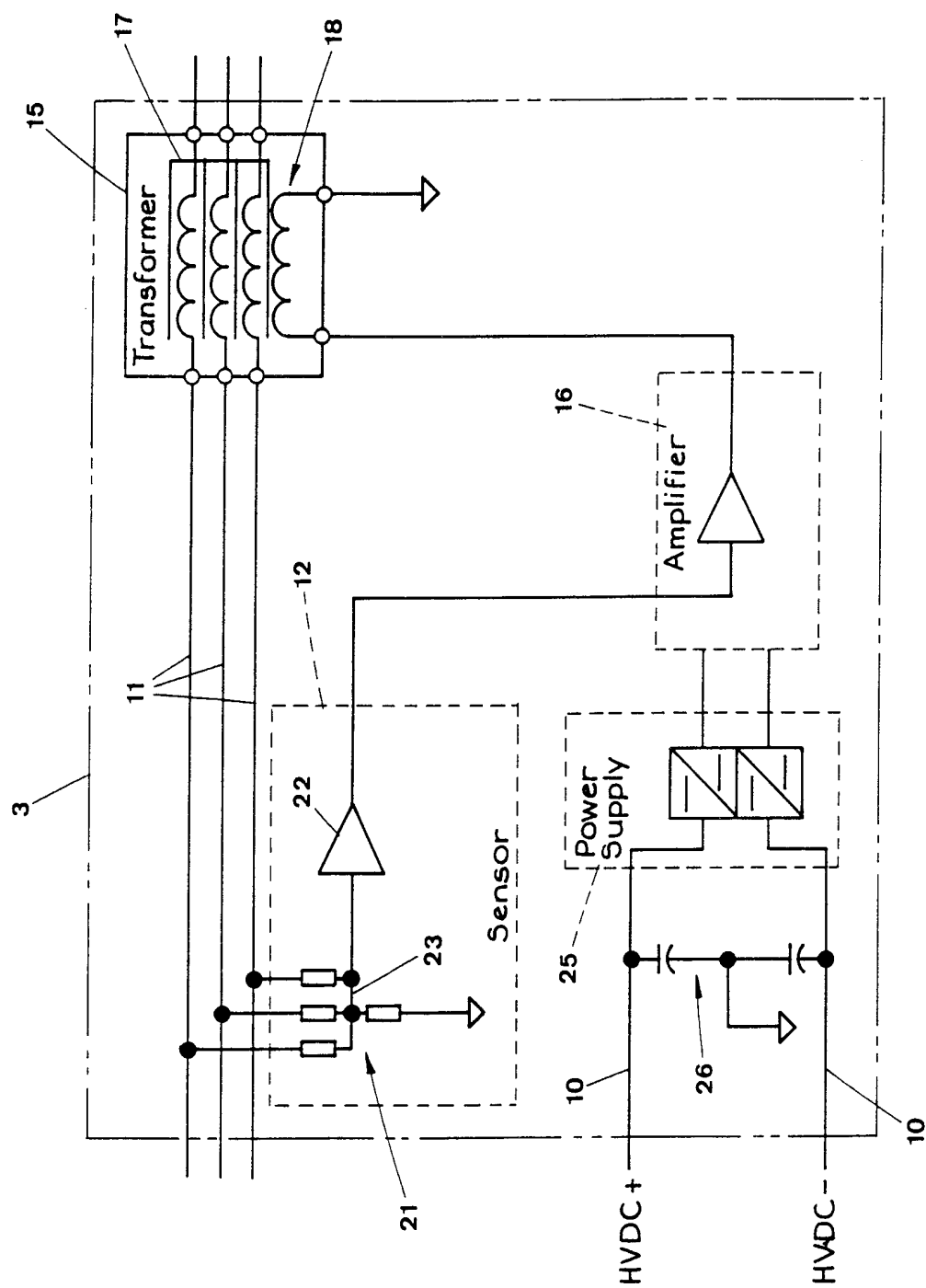


Figure 2

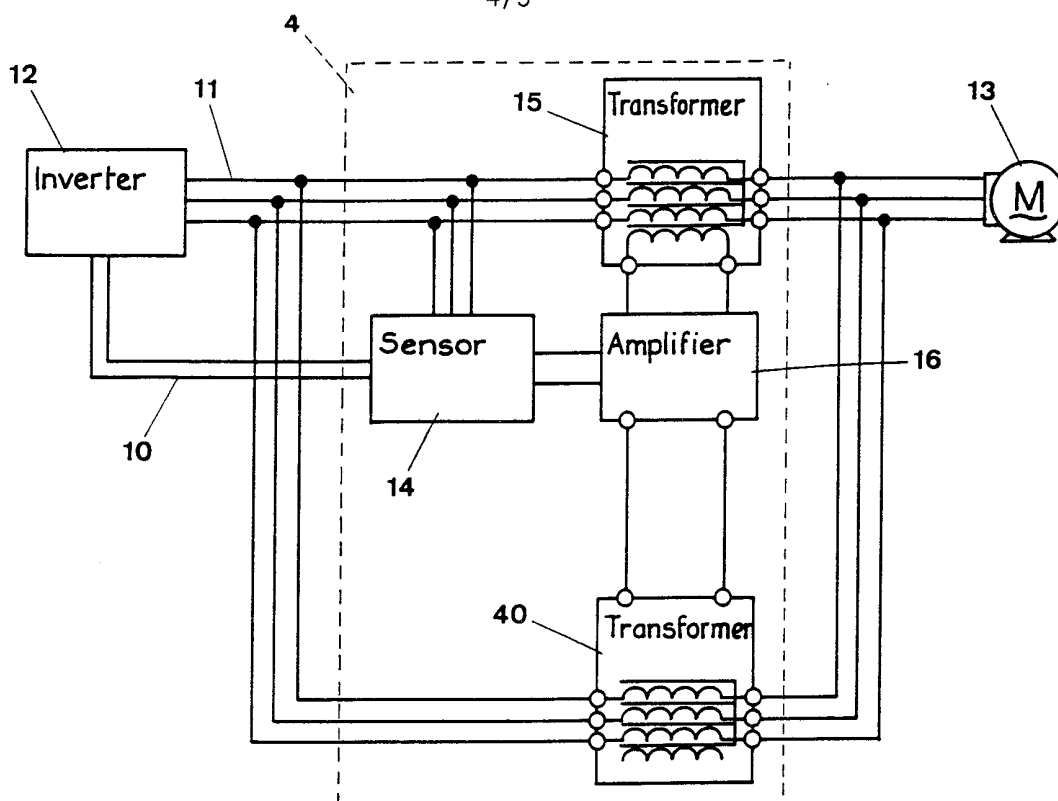


Figure 4a

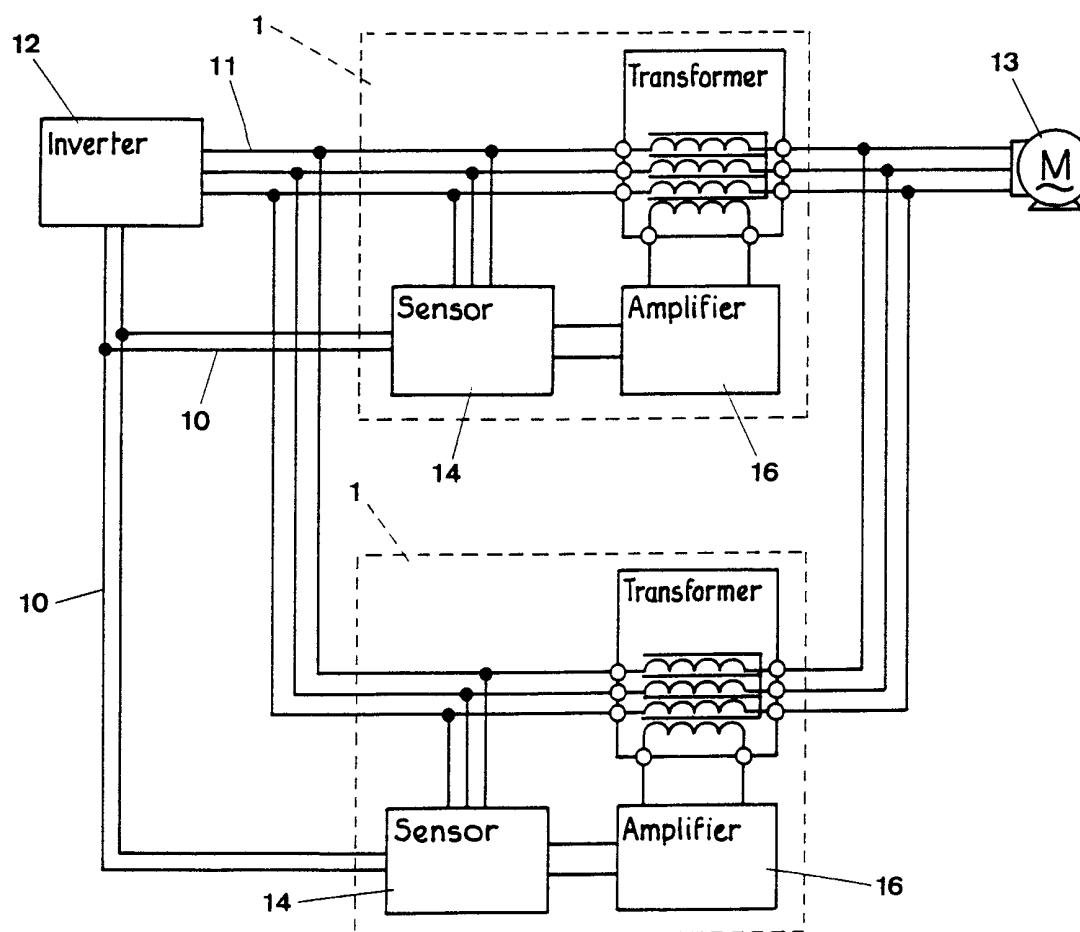


Figure 4b

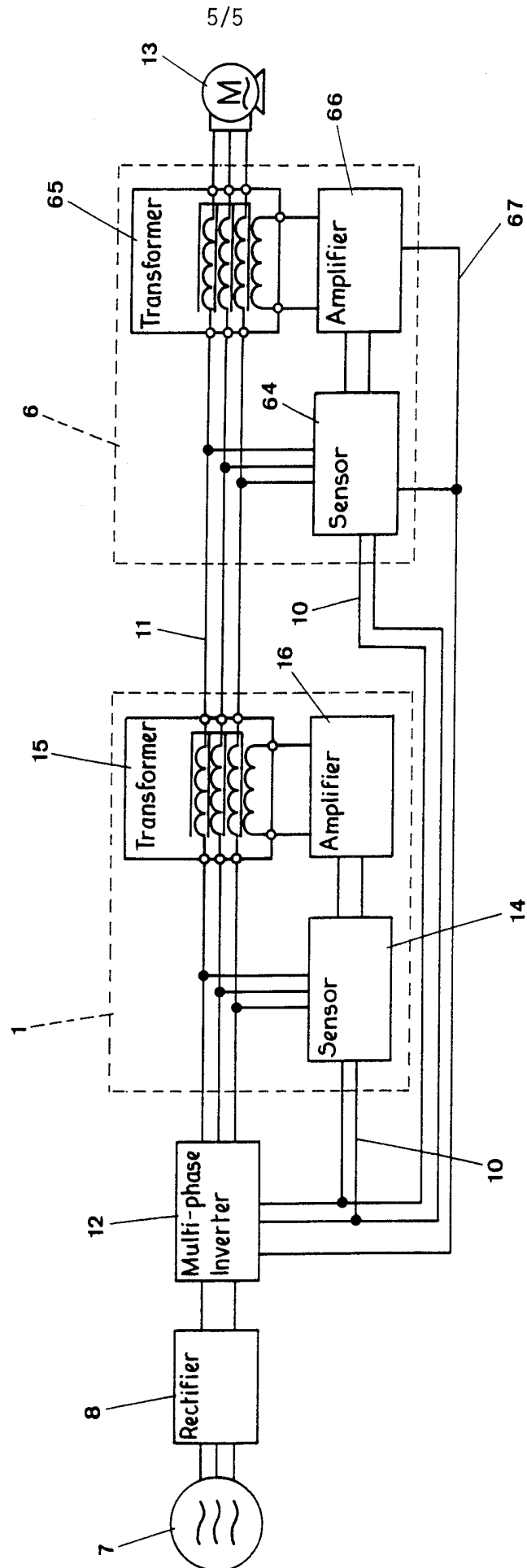


Figure 6